State of the Art on High Voltage Metrology: Past, Present and Future

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Article Type: Review article.

Abstract

High voltage measurements are not only significant for reliable transmission of electricity at high voltage potentials but also play a vital role in different realms and various applications. Their most common applications are in power electronics, medical technology, electromagnetic compatibility, particle accelerators, aluminum production, and electronic ignition systems. High Direct Current (DC) and Alternating Current (AC) measuring devices for high voltage are extensively used in numerous claims. Precise high voltage measurement techniques are crucial to guarantee these measuring devices' performance, assess their standard operating procedures and ensure their measurements' quality. High voltage metrology validates inclusive progresses in science and technology. To comprehensively understand these developments, it is essential to know the high voltage history, its main aspects, and its measuring techniques timeline growth. This state of the art introduces the history and the principles of the high voltage science. Recent measurement techniques and advances in the high voltage metrology are provided. Moreover, future trends in high voltage metrology and precise measurements are discussed.

Keywords: High voltage, Precise measurements, Metrology, Power Generation, Transmission, Insulation, Optimization

1 Introduction

High voltage is a generic term that includes all voltages higher than one kilovolt [1]. Nowadays, high voltage technology has an extensive range of applications. Huge amounts of electrical energy are transmitted at high voltages. Alternating high voltage has a special importance as electrical power is mainly transmitted in high AC voltage. Hence, high AC voltages are needed in different physics and engineering applications including generating high DC voltage and impulse systems. Besides, high AC voltage is applied in insulation tests such as insulators' properties and partial discharge detection [2].

High voltage measuring techniques and tests should be able to measure all the apparatuses of power systems' high AC and DC voltages. Traceable high DC voltage measurements with low uncertainties become progressively significant because of broader introduction of high DC voltage transmission lines [3]. Development of measurement techniques of high voltage is essential to ensure the consistent transmission of electrical energy, protect electrical devices from breakdown, guarantee the power quality, monitor, and evaluate the power flow in the power systems. The high voltage devices should have to be exposed to a series of tests to give satisfactory information about their reliability and lifetime. All tests need accurate and precise measurement techniques as well as calibrated measuring systems. Thus, all high voltage measuring devices should be precisely calibrated taking into consideration their measurement uncertainties to achieve their best calibration and measurement capabilities (CMCs) [4].

The generated high AC voltages are used to calibrate the electrical sourcing and measuring systems as well. Science of metrology fulfils these needs and unifies the measurement language worldwide via international recognition. High voltage metrology does not only support industry, research, and development to deliver accurate and precise measurements but also provides the traceability to the international system of units (SI) for these measurements. Precise measurements play a strategic role in saving energy [5]. The main calibrations, tests and measurement procedures for the high voltage devices and systems are stated in the international IEC 60060 test standards series [6–8]. IEC 60060-1 standard is for the terms and requirements of AC test voltages generation [6]. AC voltage calibrations and measurement procedures are described in IEC 60060-2 [7]. Definitions and requirements for on-site tests are specified in IEC 60060-3 [8]. Before going through the high voltage present and future measuring techniques, its history and main aspects have to be introduced.

2 High voltage History and Main Aspects

The importance of electrical power generation was recognized immediately after the development of the electric generator. The first public power station (plant) was established in London. Initially, there were limited systems that produced low DC voltages and currents. They were only used for electric lighting in neighbouring areas. In 1886, Nikola Tesla used the step-up transformers to obtain higher AC voltages. Accordingly, longer lines were used to supply power to inaccessible areas. By 1890, AC voltage sources, generators and transformers were competing with earlier DC systems. The first main AC power station was built in 1890 to deliver 10 kV electrical powers 28 miles to central London. Although transmission voltage levels were limited for economic reasons, growing the demand for electrical energy and the necessity to transmit power over long distances increased transmission voltage levels [9].

Edison was promoting for the DC voltage, and he stated that AC voltage was not effective in most cases while Tesla didn’t agree with Edison in this regard. Essentially, most electrical transmissions are made on AC systems. AC voltage is professionally and economically transmitted from power plants via transmission lines more than DC voltage. However, overhead high voltage direct (HVDC) transmission lines, submarine cables, and cascading installations are preferred as they give smart technical and economic solutions for bulk power transfer for long distances. Moreover, HVDC transmission offers a higher power density compared to AC transmission. Also, HVDC is used for testing HVAC cables of long lengths because testing by HVAC requires very large current values. Power electronics progress supports the growth of DC power transmission systems [10]. Hence, AC voltage is converted into DC to be compatible with all DC appliances [11]. Consequently, AC to DC converter is needed to enable efficient conversion for these power devices [12].

By the end of the nineteenth century, power demand was increased, and people started to build power production centres. With the development of the manufacturing technology and the growth of power applications, advanced power stations have appeared.

Within few years, many power stations were constructed in central cities of America, Europe and South Africa. Different kinds of energy such as fossil fuel, nuclear fuel, hydraulic and wind were converted into mechanical energy in power stations. Subsequently, this mechanical energy was converted into three-phase electrical power.

Over the past century, the efforts of electrical power engineers all over the world were continued to develop reliable power systems considering the networks' size and the environmental conditions effect. Electrical power is generated at power stations (plants) and transmitted to the distribution substations using transformers, transmission lines and transmission substations. Subsequently, distribution substations distribute the electrical power to the domestic consumers.

The electric power system main components are the generation plant, step-up distribution substation, step-down distribution substation and transmission lines [13]. Electrical power plants (stations) are utilized to supply the power to the electrical grid. Most of these stations convert the mechanical energy into electrical energy by using generators except for the renewable power plants [1].

Thermal and renewable plants are the two main types of generation power stations. Thermal power plants use fuel to heat the water and produce a highly pressured steam to rotate the turbine which turns the generator. Thermal energy is created in fossil fuel power plants by burning the fuel while nuclear plants use the nuclear fission technique. Solar thermal plants use the sun heat to generate the steam that is used in rotating the turbine. Renewable plants develop their energy from their own movements to generate electricity. Eventually, these energy sources renew themselves; however, their quantities are limited. Most common renewable power plants are hydroelectric, solar and wind.

Hydroelectric plants generate electricity from falling water while solar plants use photovoltaic cells to create electricity. Wind power plants produce electricity from wind by transferring kinetic energy to the turbine.

After generating electricity, step-up transformers are used to step the voltage up to a higher voltage to be transmitted for long distances with minimum power loss. The transmission of electrical power from power stations and substations to the urban centres takes place through overhead transmission lines at high voltage to keep the transmission losses as low as possible. Transmission system is the system that links generation plant station to consumers over the distribution system. Overhead transmission lines (TLs) are started at the step-up transformer and ended at the substation step-down transformer. Practically, three phase three TL system is applied in transmission system; in the meantime, three phase four TL AC system is applied in distribution system. Conductors, towers, and insulators of transmission lines are essential elements in the transmission system as well as the transmission insulation protection against partial and complete failures.

Electrical power distribution system is responsible for providing the power to different consumer premises with a much lower voltage level compared to the high voltage that has been transmitted over long distances.

Distribution of electric power is performed via a distribution network. Distribution network provides the electrical power from transmission system and distributes it to the consumer via small substations. In the urban areas, the energy is distributed through underground high voltage cables and Gas Insulated Lines (GIL). Ring distributors overcome the radial ones' drawbacks as if one feeder is under fault, the ring distributor will be energized by other feeders. As a result, the consumers will not be affected even when any feeder becomes out of service. Moreover, if any fault occurs on any part of the ring distributor, this part can be directly isolated by opening the ring distributor isolators.

Insulators are strongly affected by environmental conditions because they are used in outdoor applications. Accumulation of pollutants on the insulator surface in the presence of rain or moisture creates a conductive layer. As a result, a leakage current is produced. At high voltages a partial arc is formed and connected the insulator two metal electrodes producing a flashover. Overhead TL insulators flashover leads to the reduction of the reliability of the electric power grid. [14, 15]. Leakage current is the most effective factor in occurrence of insulator flashover. Flashover depends on the type of pollution and time duration that the insulator is placed in the polluted environment [16]. Industrial, desert, and marine pollutions are the main three types of TL insulator pollution [17, 18]. Industrial pollution is caused by industrial plants which produce pollutants such as chemical particles, dust, carbon, and cement and deposited on the insulator surface. These pollutants may lead to flashover when mixed with moisture or water. Desert pollution is formed due to accumulation of dust, sand and sometimes salty which travelled to the insulator surface by wind or sandstorms. This type of pollution leads to reduction of the efficiency of the power line network. Marine pollution is produced in coastal areas due to the growth of the salted dew from the sea creating a conductive polluted layer on the insulator surface. The deposition of sea salt on insulator surface depends on the speed of the wind and distance from sea [19].

Several methods are applied to evaluate and monitor the pollution level on the insulator surface. Partial discharge (PD) is a limited to a small area breakdown (BD) under high voltage. Partial Discharge (PD) is simply a flashover of an insulator portion due to a local increasing of electric field over the insulator withstand capability while the rest of the insulator remains able to withstand the applied electrical field. During manufacturing process of overhead TL insulators small air voids, or cavities may be formed. Partial Discharge (PD) takes place due to the existence of these cavities. Consequently, PD leads to degradation and failure of the insulation of the transmission lines [20].

Partial discharge phenomenon is classified into three main types. These types are corona, surface, and internal discharges [21]. Many aspects must be considered at higher voltages to avoid destroyed insulation. If higher voltages are applied on an insulator at a certain electric field insulator resistivity drops and the current flows through causing an insulator breakdown. The insulator breakdown voltage is the least amount of voltage that converts an insulator to a conductor. It is a form of an insulation failure that takes place when the electric field becomes high enough to liberate insulator electrons. The free electrons are accelerated by the electric field and hit other atoms, resulting in more free electrons in a chain reaction, causing the insulator to be flooded with charged particles.

Protection system is responsible for protecting electrical circuits from failures and faults by isolating the faulty parts from the circuit. Normally, protection devices are used to implement the protection scheme.

Circuit breakers are the most effective device in any protection system. They are responsible for closing and opening the electrical power system depending on relays orders. The sizes of circuit breakers vary from small circuit breakers that protect small household appliances to large switchgear that protect high voltage circuits. The bus-bar circuit breaker is tripped off as soon as any fault occurs, and the faulty part is disconnected from the power system. Single busbar is commonly used in the small substations while additional busbar is used in large substations to avoid interruption occurrence in their supply.

Relay is the brain of a protective system. If a fault occurs, the relay sends a signal to the circuit breaker for disconnecting the faulty part from the rest of the electrical system. The relay opens and closes an electric circuit either electronically or electromechanically. To protect transmission lines, directional relays are used where the power flow is related to a specific direction [26]. Directional relays play a vital role in distribution grids [22, 23].

3 Present Experimental and Optimization Techniques of HV Precise Measurements

Fundamentals, main aspects, and old measuring techniques of high voltage are still valid till now. More recent advances are combined with these ancient techniques taking into consideration the digital measurement and data transmission technologies to give the present measuring techniques. Nowadays, the demand for accurate, precise, and traceable measurements of voltage at higher levels has been increased due to the excess of high voltage grids and transmission lines. Moreover, AC and DC high voltage measurements play an energetic role in many science and instrumentation fields. Rapid and continual growth in high voltage measurements offers superior measurement accuracy and uncertainty [24].

Measuring devices of high voltage have to be able to deliver accurate and precise reduced voltage signals. High voltage measuring systems are divided into voltage transformers and dividers. Voltage transformers are used in substations, while voltage dividers are mostly used in laboratories. Regular calibration of high voltage measuring systems is a very essential requirement of many governmental and private sectors. Accordingly, traceable measurements of high AC and DC voltages to SI units with minimal uncertainty values become more essential because of extensive establishment of transformers, transmission lines and distribution systems. Moreover, the different stresses that may arise during real-world operation of the high voltage measuring systems are simulated using various optimization techniques in laboratory and on-site as well [25].

Regular calibration of high voltage measuring systems is an essential need of many governmental, educational, and private sector industries to ensure accurate electricity standards and enable robust measurements. Besides, traceability of measurement results to a higher standard with specified uncertainties is essential to confirm the consistency of measurement results [26].

3.1 High Voltage Divider Experimental Measuring Technique

Generally, high voltage measurements include the use of a voltage divider to provide the high voltages in the ranges that can be measured by a meter or an oscilloscope [27]. The high voltage measurement criterion is mainly based on precise low voltage measurements. Normally, calibration of a complete high voltage measuring system that consists of a high voltage divider and a display has been achieved by comparing this system with a reference standard system in order to maintain its traceability to the international system of units (SI). Consequently, calibrations of dividers and displays of high voltage systems up to the highest transmission voltages are crucial.

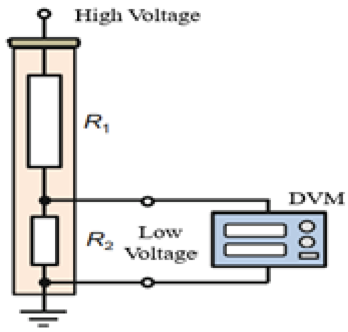
The high voltage measurements traceability is normally attained using resistive or capacitive voltage dividers. Thus, reference resistive and capacitive dividers have been constructed by numerous national and international laboratories taking into consideration different influences. Different designs of high voltage reference dividers have been developed [28-32]. The precision of the DC high voltage dividers depends on a resistive design, while the AC high voltage dividers precision generally relies on a capacitive design. The traceability of DC high voltage measurements to SI units is generally attained using resistive voltage dividers. The precise resistive divider consists of several resistors connected in series [3].

High DC voltage dividers are calibrated at low voltage via the DC Josephson Voltage Standards (JVS) [33]. Capacitive high voltage divider consists of two capacitors: one on the high voltage side and the other on the low voltage side. In the same manner, resistive divider consists of two resistors. Insignificant parasitic resistance is comprised in the capacitive divider [34]. Figures (1-a) and (1-b) show resistive and capacitive designs, respectively. The widespread high AC voltage measuring system consists of a capacitive high voltage divider whose output low voltage is recorded by a measuring instrument.

In the past, high voltage measuring instruments in conjunction with high voltage dividers were completely analogue. Afterwards, they have been continuously enhanced in their measurement capabilities. Nowadays, measuring instruments mostly used are digital ones based on analogue to digital converters. Digital voltmeters are typically used to measure low voltages up to 1000 V [35].

In consequence, high voltage dividers and digital voltmeters should be frequently calibrated to ensure their measurements traceability to SI units. The voltage divider is regularly used to calibrate high voltage sources. It gives a ratio that communicates the unknown high voltages to the well-known low voltages. This is realized by decreasing the high voltage to the values that can be measured by the digital voltmeter. The most common technique to calibrate the dividing ratio of the voltage divider is to acquire the ratio between actual voltages on the divider high and low voltage arms. In other words, the actual high voltage values of a voltage source are obtained by multiplying the voltages on the low voltage arm by the actual dividing ratio. The Josephson Voltage Standard (JVS) is used as the DC voltage primary standard. Traceability of DC and AC voltage measurements is achieved at the National Institute of Standards (NIS) via a DC-JVS.

Uncertainty of DC and AC high voltage measurements is significantly enhanced using the JVS. Voltage dividers are used to step high voltages down to be measured by voltmeters. Consequently, the dividers must be calibrated to get their actual and precise dividing ratios [36]. The most common process used to get the actual dividing ratio is to get the ratio between the actual voltages on the high voltage and low voltage arms of the divider. Dividing ratios of the AC high voltage dividers are typically obtained by the capacitance ratio between the output and input voltages [37-39].



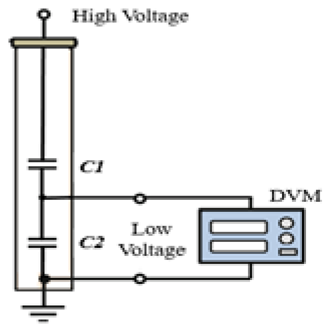


Figure 1-a: Resistive Design **Figure 1-b:** Capacitive Design

Figure 1: Resistive and capacitive designs of high voltage dividers

3.2 *Partial Discharge Detection Experimental Methods*

Insulation tests are essential in high voltage measurements realm. One of the most important tests is the partial discharge detection. Partial discharge measurements detect the failure across a void in a dielectric. This failure location is usually unknown. The partial discharge phenomenon is complicated. It was known for decades, however; it is not fully understood till now. Probability of risks and failures occurrence is always there if the partial discharge exceeds its specified values for each device.

Therefore, partial discharge continuous monitoring progressively takes place to detect the devices failure in appropriate time. The traditional method for detecting the partial discharge is performed according to the international standard IEC 60270 [40]. In this method, current or voltage pulses are produced from the test object in which the partial discharge occurs. This method is only used in high voltage laboratories with frequency bandwidth less than 1 MHz [40]. It is used in measuring the partial discharge for cables, insulators, and transformers. Electric field detection technique is one of the most effective outdoor methods used in detecting the insulation partial discharge and any other faulty insulators [41].

In this technique, the electric field simulation models are used to evaluate the distribution of the electric field over the insulators [42-45]. The electric field simulation models are linked to the experimental measuring data gathered from a tested string of insulators [41]. An electric field sensor is used to capture the electric field around the insulator string. Then the collected data are sent to a data logger or an oscilloscope via a coaxial cable to be analysed. Leakage current has a significant role in the partial discharge occurrence [14]. Outdoor insulators can be monitored by leakage current detection methods. Some of these methods are carried out in laboratories and others are performed on-line under operating voltage and environmental conditions.

This method is commonly used in transmission lines which are subjected to extreme and varying pollution conditions [46]. The controlled fog chamber is one of the laboratories measuring approaches for leakage current [14]. A High Frequency Current Transformer (HFCT) technique is used in detecting the leakage current of overhead transmission insulators [47]. In this technique, the leakage current on the surface of the insulator is measured by a high frequency current transformer in which its secondary is connected to a data acquisition system (DAS) for analysis process. Furthermore, the HFCT sensor is used for on-line partial discharge detecting in high voltage installations. This sensor is placed around the grounding conductor and the partial discharge current pulses presents the sensor input and the induced voltage presents its output signal [48]. Figure 2 shows schematic diagrams of the common partial discharge detection methods.

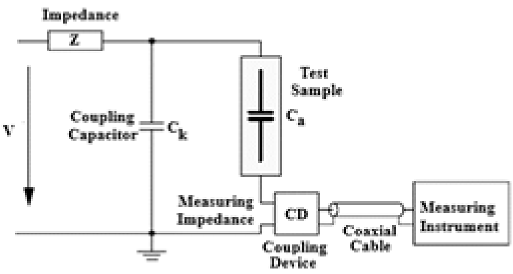


Figure 2-a: Traditional method

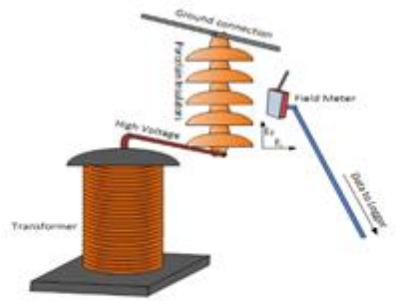


Figure 2-b: Electric field method

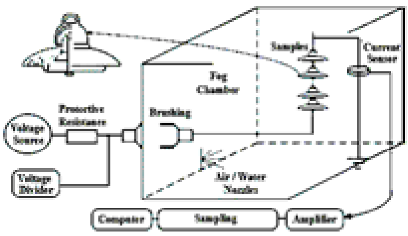


Figure 2-c: controlled fog chamber method

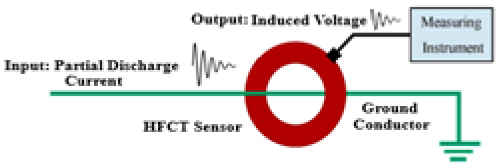


Figure 2-d: High Frequency Current Transformer method

Figure 2: Schematic diagrams of common partial discharge detection methods

3.3 Determination of High Voltage Optimum Magnitude and Phase Angle: Power Flow Optimization.

High voltage magnitude and phase angle are obtained from power flow (load flow) investigation which is crucial for the operation and planning of the power systems. When the voltage magnitude and phase angle of busbars are well identified, TLs power flow and losses can be managed in an optimum manner. Perfect identification of the power system unknown variables is the most important step in the power flow analysis.

Normally, high voltage systems are modelled to obtain its optimum electrical parameters and operational conditions using different optimization methods. Thus, to get the power system optimal parameters, the transmission network is modelled and balance equations for active and reactive power are applied. Accordingly, a mathematical model for the power system is prepared to cover all variables of the TLs and buses of the power system [49]. Many optimization techniques are developed to analyse the power flow such as Gauss Seidel, Newton-Raphson and fast decoupled power flow techniques. These methods are extensively used in power systems and TLs operation.

Nowadays, power flow methods are improved. Backward forward sweep method is used to overcome earlier techniques problems and to calculate the bus-bar voltages. Compensation-based method is prepared more adaptive for many active simulations. Also, a sensitivity-based method is presented to achieve the characteristics of generators. A new matrix is used to implement the power flow calculations in some iterative steps. Additional load flow method is applied by using a numerical expression of voltage to solve other methods difficulties. Software packages, graph theory and flexible power flow graphical methods are established to analyze the power flow [50-57].

3.4 Optimization Techniques for Fault Direction Detection: Directional Relays

Photovoltaic is one of the best choices for energy generation [61]. Widespread investigation of Photovoltaic (PV) systems before being installed within the different applications is crucial [62]. Furthermore, PV modelling is needed in many applications. PV power generation is affected by environmental conditions in nonlinear manner [63]. There are deterministic and heuristic techniques to estimate PV parameters. Deterministic technique is an iterative method which is relied on Newton's process. Gauss– Seidel iterative method, Lambert W Function, and modified nonlinear least error squares approximation methods are common deterministic methods used. Deterministic techniques have some complications due to their fast response to initial conditions small changes which distress their precision, stability, and consistency [64-66]. Therefore, heuristic techniques are preferably used to get the PV electrical parameters. Particle Swarm Optimization (PSO), self-adaptive teaching–learning-based optimization (SATLBO), Harmony Search (HS), grouping-based global harmony search (GGHS), innovative global harmony search (IGHS), Cuckoo Search (CS), Simulated Annealing (SA), and Pattern Search (PS) are the common heuristic algorithms [67, 68].

4 Future Trends in High Voltage Metrology Measuring Techniques

Although there are many well-established tools, systems, and high voltage measurement techniques unforeseen complications are occurred. Hence, new technologies are needed in building more reliable systems and innovative measurement techniques. Some of the newest measuring techniques are presented in the following sections.

4.1 Innovative Experimental Measuring Technique for High Voltage Dividers

Innovative measuring and calibrating technique using two similar capacitors is proposed for precise and traceable high voltage measurements at the National Institute of Standards (NIS) [69]. In this concern, two 100 pF capacitors are utilized to work as two identical AC high voltage capacitive dividers. The proposed measuring and calibration techniques are divided into three main setups. The first setup is to get each capacitor actual dividing ratio by individually calibrating them against the traceable reference standard for 100 kV AC voltage. The second setup is connecting the two capacitors in series and calibrating them together via the 100 kV reference standard to attain their actual dividing ratios up to 100 kV only. The dividing ratios from 100 to 200 kV have been precisely achieved using an empirical formula. Each capacitive divider of the two identical capacitors used in this work consists of two capacitors one on the high voltage side (C) and the other one is on the low voltage side (c). As a consequence of calibrating each capacitor via the Phenix-KVM100, actual high voltages (VC1,VC2) across C1 and C2 (from 10 kV to 100 kV with 10 kV step) have been acquired via the display of the Phenix- kVM100 reference standard while corresponding actual low voltages (Vc1 ,Vc2) across c1 and c2 have been measured by the HP-3458A traceable DVM. Dividing ratios ɼ(C1) and ɼ(C2) have been obtained according to equations (1) and (2).

Equation (3) presents the relation between the total voltage VT (voltages across the two series capacitors) and each capacitor voltage. Dividing ratio of both capacitors together is ɼs(C1+C2) as existing in equation (4). Dividing ratio equations are listed from (1) to (6) [69].

$$ɼ(C1) = \frac{V_{C1}}{V_{c1}} \quad (1)$$

$$ɼ(C2) = \frac{V_{C2}}{V_{c2}} \quad (2)$$

$$V_T = V_{C1} + V_{C2} - V_{c2} \quad (3)$$

$$ɼ_s(C1 + C2) = \frac{V_T}{V_{c1}} \quad (4)$$

$$V_{c1} \times ɼ_s(C1 + C2)_{atV_T} = V_{c1} \times ɼ(C1)_{atV_{C1}} + (V_{c2} \times ɼ(C2)_{atV_{C2}}) - V_{c2} \quad (5)$$

$$ɼ_s(C1 + C2)_{atV_T} = ɼ(C1)_{atV_{C1}} + (\frac{V_{c2}}{V_{c1}} \times ɼ(C2)_{atV_{C2}}) - \frac{V_{c2}}{V_{c1}} \quad (6)$$

The following equations are gained [69] to calculate the uncertainty of the actual dividing ratio of each capacitor adding to the two series capacitors ratio according to GUM [70-72]:

$$\text{Let } \frac{V_{c2}}{V_{c1}} - Z$$

$$Z = \frac{ɼ_s(C1 + C2)_{atV_T} - ɼ(C1)_{atV_{C1}}}{ɼ(C2)_{atV_{C2}} - 1} \quad (7)$$

$$U_{ɼ(C1+C2)}{}^2 = (\frac{dɼ(C1 + C2)}{dɼ(C1)})^2 \times U_{ɼ(C1)}{}^2 + (\frac{dɼ(C1 + C2)}{dɼ(C2)})^2 \times U_{ɼ(C2)}{}^2 + (\frac{dɼ(C1 + C2)}{dZ})^2 \times U_{(Z)}{}^2 \quad (8)$$

$$\frac{dɼ(C1 + C2)}{dɼ(C1)} = 1 \quad (9)$$

$$\frac{dɼ(C1 + C2)}{dɼ(C2)} = Z \quad (10)$$

$$\frac{dɼ(C1 + C2)}{dZ} = ɼ(C2)_{atV_{C2}} - 1 \quad (11)$$

$$U_{ɼ_s(C1+C2)}{}^2 = Uɼ(C1)_{atV_{C1}}{}^2 + Z^2 \times Uɼ(C2)_{atV_{C2}}{}^2 + (ɼ(C2)_{atV_{C2}} - 1)^2 \times U_{(Z)}{}^2 \quad (12)$$

The last setup is calibrating a 200 kV AC high voltage measuring system by means of the two calibrated capacitors according to IEC 60060-2:2010 international standard [73]. AC High voltage source is utilized to supply the high voltage side in all calibration setups [74, 75]. Figure 3 displays the two series capacitors calibration setups up to 100 kV.

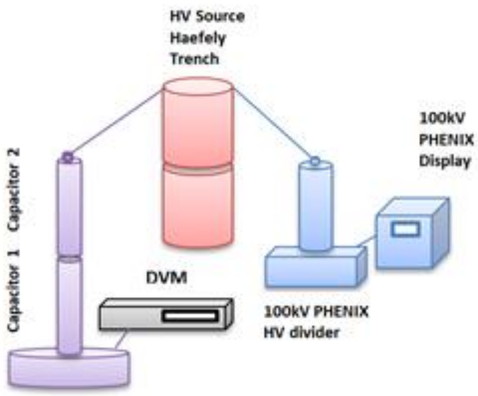


Figure 3: Two series capacitors calibration setup

With the same manner, the high voltage dividers proposed measuring technique and the designed extrapolation imperial formulas can be applied for other high voltage measuring systems with different ranges.

4.2 RF Radiation Experimental Technique for Detecting the Partial Discharge

In principle, partial discharge occurrence returns to the fast movement of free electrons. The electron acceleration not only produces the leakage current effect, but it also generates radiating electromagnetic waves. So, when a partial discharge happened due to defective insulators, electromagnetic waves which known as Radio Frequency (RF) signals are emitted from the insulators. The radiated signals are captured by antennas or sensors with special bandwidth [76]. Very High Frequency (VHF) and Ultra High Frequency (UHF) sensors are applied to detect the partial discharge [40]. Recent publications show that the sensitivity of the UHF partial discharge detection technique in identifying and locating the failures is better than other detection methods [77]. UHF sensor with bandwidth of 300 MHz to 1.5 GHz is proposed to detect the partial discharge in TL insulation. In this proposal, electromagnetic waves with signatures of outdoor insulator defects are captured and transmitted to a 500 MHz oscilloscope. Then, an intelligent classifier is designed to classify and identify the type of outdoor insulators defects. Figure 4 shows a schematic diagram of the partial discharge detection setup. In addition, a simulation model is developed for expecting the partial discharge before its occurrence. Different artificial faults are applied to the insulator discs and their equivalent RF signatures are captured using a high frequency sensor under the regular operating conditions. Discrete wavelet transform is used to extract several features from the captured signals. ANOVA variance test is performed to assess the capability of each feature in identifying the fault and classifying its type.

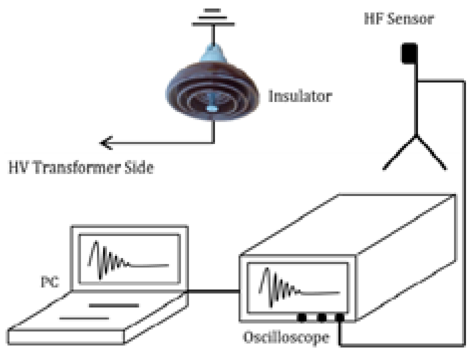


Figure 4: Schematic diagram of the partial discharge detection setup

In the near further, the high voltage insulation properties will be considered such as the insulation resistance, conductivity, capacitance, and dissipation factor.

4.3 New Optimization Technique for Investigating the Power Flow

Time efficient power flow technique is proposed to be employed in the distribution systems that have Voltage Dependent Loads (VDLs) [78]. This technique is suggested to determine the high voltages directly from the load injected currents in a reduced time. Prior power flow techniques assumed that the consumer active and reactive power loads are constant nevertheless the load types. However, different types of loads (domestic, commercial, and industrial) are presented. These loads are mainly depending on the voltage, so they are classified as VDLs. In this case, the injected currents should be individually measured for all load types. Hence, the proposed technique is developed based on the concept of the Load Injections to Bus Voltage (LIBV).

The LIBV matrix procedure is anticipated using five buses balanced Radial Distribution System (RDS) network. This proposed LIBV matrix makes a relation between the load injected current and its voltage. Iterative procedures are used to solve the load flow complications. The initial bus-bar voltage values are firstly estimated based on the load. The tolerance limit (ε) is well-defined. Then, the LIBV matrix is built based on the distribution system construction. The simplification of the proposed technique in this iterative way is explained in the flowchart shown in Figure 5. Also, an annual growth in the load is studied to sustain an effective operation of the power distribution system. The proposed technique validity is examined by analysing a complex load model which consists of pumps, fans, fluorescent lamps, incandescent lamps, and motors. Then, the obtained results are compared to the literature reported results for the similar model. It is found that the proposed technique shows about two times faster than other techniques.

Moreover, the precision of the proposed technique is verified by applying it on two balanced RDSs for different load models. The first balanced RDS system is a 30-bus while the second one is a 33-bus. Figure 6 (a, b) illustrates the behaviour of balanced RDS systems (with and without load growth at constant current loads) for 30-bus and 33-bus respectively. Consequently, the obtained results prove the effectiveness of the proposed technique compared to the results of previous approaches. Besides, the proposed algorithm is more robust and faster than the conventional techniques. In future, this new optimization technique can be applied to more complicated electrical power systems to obtain their best power flow constrains.

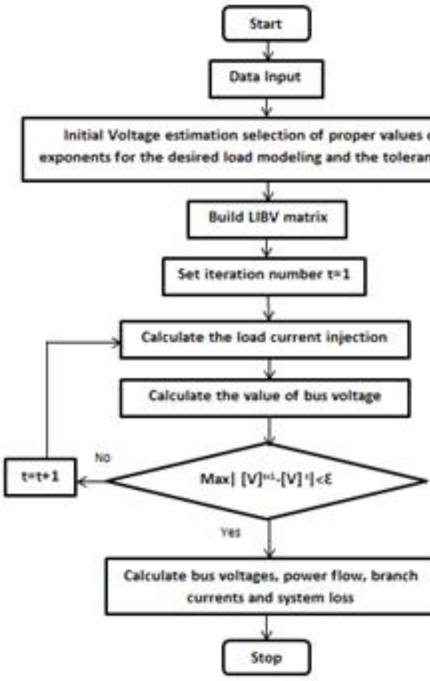


Figure 5: Flowchart of the proposed power flow technique

results of the work, don't repeat them. Avoid extensive citations and discussion of published literature only; instead discuss recent literature for comparing your work to highlight novelty of the work in view of recent development and challenges in the field.

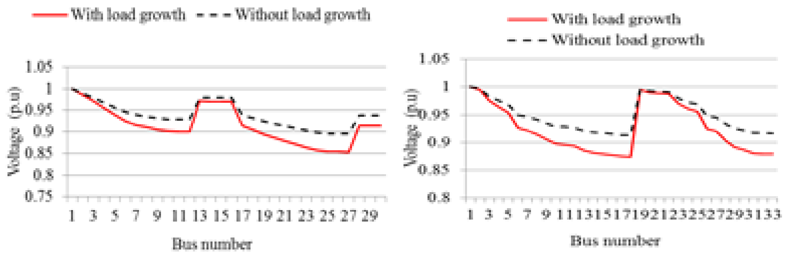


Figure 6-a: 30-bus system **Figure 6-a:** 30-bus system

Figure 6: Balanced RDS systems behaviour with and without load growth

4.4 Innovative Optimized Protection Systems

4.4.1 New Current Dependent Directional Relay

A new protection system is proposed for detecting the fault direction depending on the current signal only with no need for the voltage signals [79]. Normally, the fault direction changes the phase angle polarity. If the pre-fault current changes its normal condition direction, the phase angle will be changed by 180 degrees. Hence, the pre-fault phase angle is precisely measured in this technique to identify the fault direction. Then, the difference between the fault and the pre-fault angles is determined. The pre-fault data samples are applied when the fault occurred. Logic circuit of the proposed protection system is shown in Figure 7, where A and B are the pre-current and present current angle difference. A=0, 1 specifies whether the power flow direction is reverse or forward. B=0, 1 show whether the current angle is smaller or greater than zero.

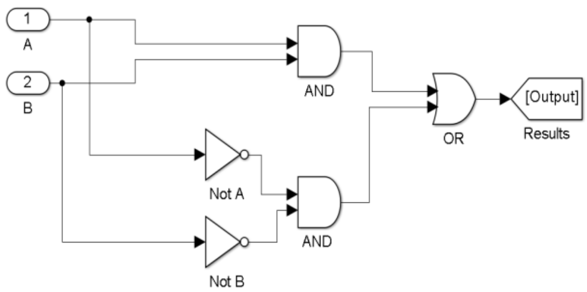


Figure 7: Logic circuit for the proposed protection system

The flowchart shown in Figure 8 describes the operation procedure of the proposed protection system. The optimization program is established using the MATLAB and the ATP-EMTP software to take an appropriate decision before occurrence of the fault. Figure 8 shows logic circuit for the proposed protection system. The flowchart shown in Figure 9 describes the operation procedure of the proposed protection system.

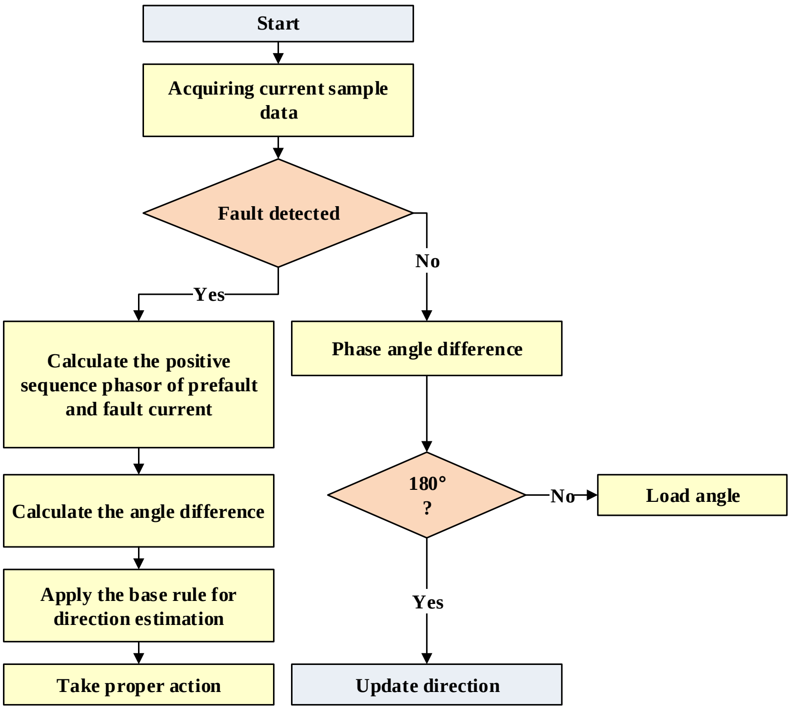


Figure 8: Proposed protection system flowchart.

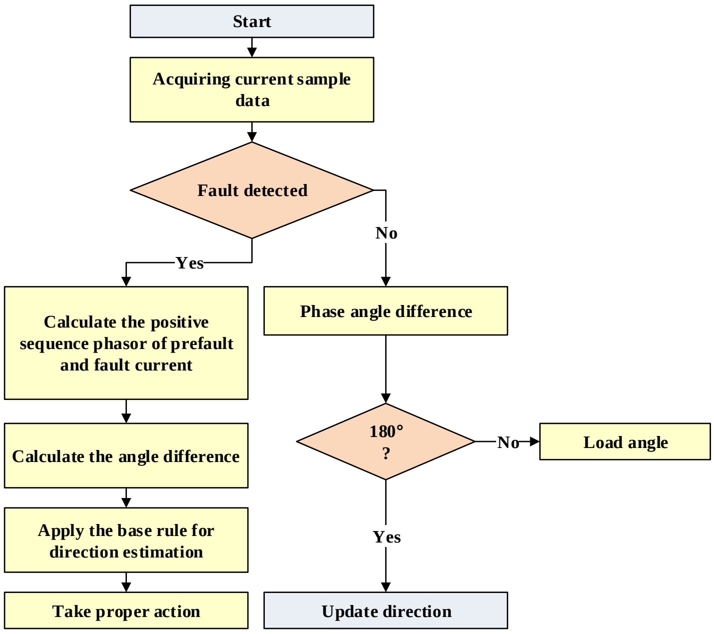


Figure 9: Proposed protection system flowchart

The optimization program is established using the MATLAB and the ATP-EMTP software to take an appropriate decision before occurrence of the fault. Many fault scenarios with different fault angles, types, resistances are performed to check the reliability of the protection system. Moreover, the new protection system is assessed under noise effects at different frequencies. The results of the proposed protection technique prove its efficiency and robustness compared to other previous protection systems.

4.4.2 Advanced Directional Relay in the Presence of a Series Compensation

The series compensators are the most promising transmission system devices that are widely used for enhancing the transmission competency. Compensator is mainly safeguarded by a Metal Oxide Visitor (MOV) that change its resistance based on the applied voltage. MOV resistance decreases if the voltage across it increases and vice versa. Most conventional protection systems are not trustworthy to define the fault direction (current and voltage inversions) for the series compensated transmission lines. Hence, an advanced directional relay is suggested for protecting the series compensated transmission lines. In this proposal, a protection system is relying on precisely measuring pre- and post-fault currents and voltages. The proposed protection technique depends on the phase change in the positive sequence current and magnitude change in the positive sequence voltage [80]. Both angles of the positive-sequence current and voltage magnitude are accurately measured. Different configurations are considered to assess the reliability of the proposed protection system. These configurations contain various capacitor ratios that reverse the power flow direction to offer different inversion scenarios for current and voltage. Different fault types are measured as single line to ground, double-line to ground, line to line and three-phase fault. Also, fault locations are varied from 10% to 90% and fault resistance is ranged between 0 Ω and 300 Ω as well. To check the performance of the proposed protection system, 13 scenarios are classified and studied. The flowchart illustrated in Figure 10 designates the operation process of the proposed protection system. Where: Sɵ: angle between the positive sequence fault and pre-fault currents, Δ|V|: magnitude difference between the pre- and post-PS voltages

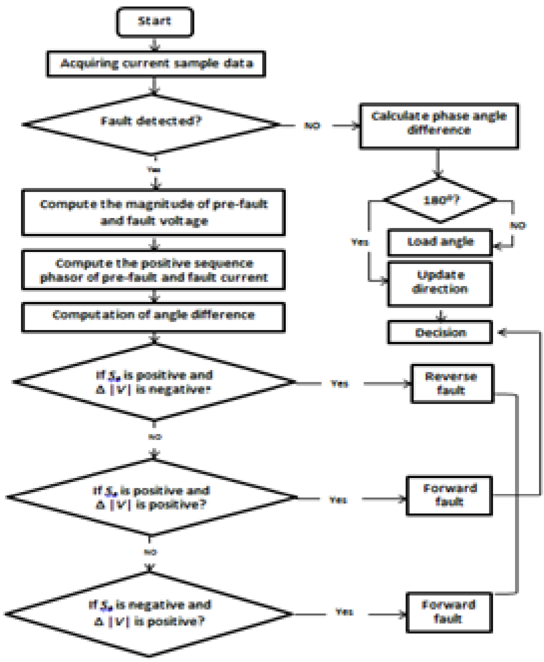


Figure 10: Flowchart of the proposed protection system

Experimental and ATP-EMTP software simulation analysis proves the consistency of the proposed protection system for any fault type and position. The competency and strength of the two proposed directional relays verify that they can be safely used soon for protecting more high voltage systems with inconstant environmental conditions and various faults scenarios.

4.5 Improved Optimization Technique for Photovoltaic

Accurate and precise PV modelling and precisely estimating the optimal electrical parameters at different environmental conditions are highly required. An improved optimization technique is proposed [81]. In this proposal, Particle Swarm Optimization technique is enhanced by Fractional Order Calculus to be applied for PV modelling. The adapted technique is called Fractional Order Darwinian Particle Swarm Optimization (FODPSO). It is built to evaluate the optimum electrical parameters of PV cells and modules. Single and double diode models are used to describe the PV modules. FODPSO and PSO algorithms are proposed to be applied on two different PV modules at various irradiances and temperatures (Figure 11). Comparison between FODPSO, PSO, and some previous optimization techniques are performed. Experimental measurements associated with their expanded uncertainties are realized for two dissimilar poly crystalline silicon modules at different irradiances and temperatures. Precision of FODPSO technique results is proved by plotting the I-V and P-V curves and comparing the FODPSO technique results and experimental ones at different environmental conditions as illustrated in Figure 12. Additionally, the current and power Root Mean Square Errors (RMSEs) adding to the Summation of the Individual Absolute Error (SIAE) results are acquired and compared by using FODPSO and PSO techniques. The results of the proposed FODPSO algorithm demonstration admirable agreement with the experimental results at different environmental conditions which verify the technique competency. This technique can be perfectly applied in future for other kinds of solar cells and modules.

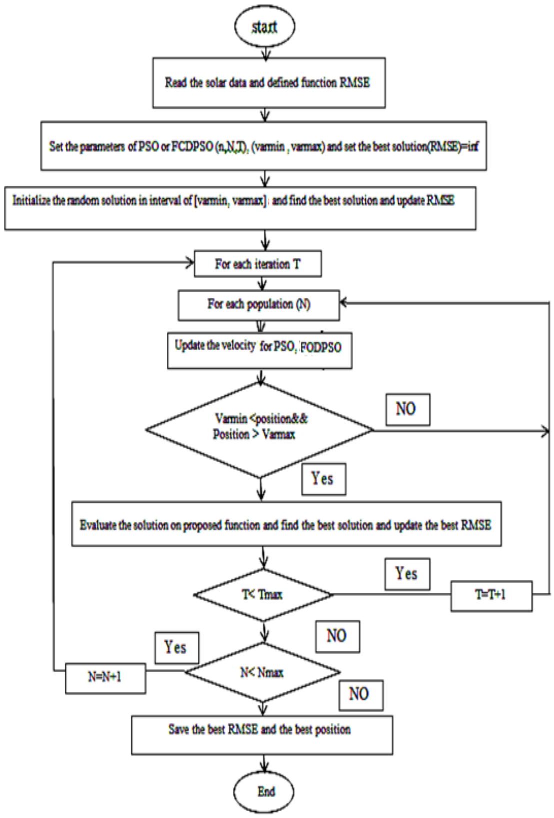
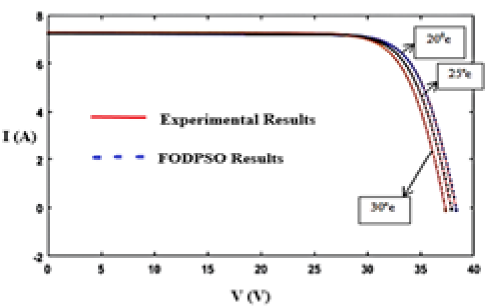


Figure 11: Flowchart of FODPSO and PSO Techniques



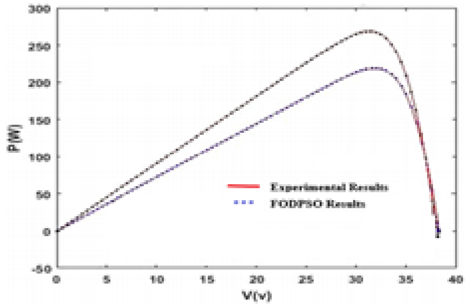


Figure 12-a: I-V curves of a single diode model **Figure 12-b:** P-V curves of single diode model

Figure12: I-V and P-V curves of a single diode model for FODPSO algorithm at different conditions

4.6 Modified Optimization for Environmental Economic Load Dispatch

Fuel cost is a considerable factor in thermal power plants adding to the operation and maintenance costs. Thus, Economic Load Dispatch (ELD) is an essential mission for power system operators [82]. Obtaining a minimum cost of electricity generation without affecting quality and reliability simply define the ELD. Increased pollution due to fossil fuel thermal plants makes environmental impacts are necessary to be considered. Therefore, the ELD is replaced by the Environmental Economic Load Dispatch (EELD). Operation cost, maintenance cost, equipment capabilities, transmission restrictions and operational constraints have to be taken into account in the design of any optimization algorithm for the EELD [83]. EELD is a multi-objective which has two main objectives [84]. The first objective is reducing the generation costs, while the second one is reducing the generating systems emissions. This proposal introduces a Modified Sine Cosine Optimization (MSCO) algorithm to solve the nonlinear EELD problems. MSCO is a modified version of the traditional Sine Cosine Optimization algorithm. The aim of this algorithm is discovering the optimal preparation of power generation system that minimizing cost and emission simultaneously without fluctuating the generation process. To validate the proposed MSCO technique, it is applied on two real systems with non-smooth (nonlinear) fuel cost and emission functions. The first real system contains 6 units (1200 MW) while the second one consists of 10 units (2000 MW). MSCO technique is compared with other common optimization approaches in literatures. The comparison results for the ten units system is listed in Table 1.

Table 1 : *Comparison between the proposed MSCO algorithm and other algorithms for the ten-unit system*.

Outputs	MODE [17]	NSGAII [17]	PDE [17]	SPEA-2 [17]	GSA [29]	ABC_PSO [30]	EMOCA [31]	FPA [16]	Proposed MSCO
Fuel Cost ($)	1,13484	1,13539	1,13510	1,13520	1,13490	1,13420	1,13445	1,13370	1,10870
Emission (Ib)	4124.9	4130.2	4111.4	4109.1	4111.4	4120.1	4113.9	3997.7	3940.6
Losses (MW)	84.33	84.25	83.90	84.1	83.99	84.17	83.56	84.30	21.48
Run time (s)	3.82	6.02	4.23	7.53	NA	NA	2.90	2.23	1.83

The proposed MSCO algorithm results show the least fuel cost, lowermost emission and losses adding to the smallest running time as well which prove the strength and efficiency of this optimization technique. Hence, the proposed MSCO is considered as a competent alternative for complicated EELD optimization techniques. The algorithm simplicity and minimum computational time are the merits of the MSCO algorithm construction over other algorithms. Thus, it can be generalized in all power systems soon.

4.7 Green Buildings

Green buildings are the buildings that fulfil the clean energy requirements with low energy consumption and less cost [85]. These buildings reduce the harmful impacts on environment and human health by decreasing the pollution and using resources in an efficient way. Construction of the green buildings maintains the balance between homebuilding and sustainable environment. In simple words, green designing is a wise process that utilizes resources to offer high quality and energy efficient buildings [86].

Using green building materials is crucial in design and construction process. Reducing heat loads, increasing natural light, and encouraging the circulation of fresh air are indicators of the respectable green building design. Furthermore, these indicators comprise energy efficient lighting and air conditioning adding to the usage of appropriate materials. Green buildings will replace the traditional ones in the coming years. A new commercial green building is suggested to be a case study for green buildings.

The proposed green building contains entrance, administration rooms, lectures rooms, work areas, offices, labs, corridors, toilets, kitchen, restaurant, and storage areas [87]. The windows of the building are double glazed, and they are positioned to take full advantages of the natural heat and light. The walls are made of glass curtain with low emissivity coatings for obtaining the best insulation. Glass curtain walls present fifty present of the building. The building and its landscape are designed to satisfy the natural ventilation necessities. The roof and walls are well insulated using durable insulation materials to eliminate leakage of the heat. Moreover, solar modules are used to generate the energy.

Optimal distribution for electrical is followed. Lighting system which contains ultra-high-power quantity with low power consumption is carefully chosen. Lamp’s power and lifetime are considered to calculate the total energy consumption of the chosen lighting system. Proficient heating and ventilating systems are installed. High Voltage Air Conditioning (HVAC) system with the technology of Variable Refrigerant Flow (VRF) [88] is applied. The HVAC system operation technique relies on the outside environmental conditions. To assess the green building consistency, a comparative study is performed between the green and traditional concepts in designing walls, windows, roof insulation, lightning and HVAC systems as listed in Table 2.

Table 2: *Comparison between green and traditional concept of designing and building.*

Building Features	Building Green Design Concept	Building Traditional Design Concept
Walls	Four brick layers	Single brick layer
	25 mm R-7 board insulation	Normal insulation
	50% Glass curtain walls + 50% normal walls	100% normal walls
	Low emissivity coatings	Normal coating
Windows	Double Glazed with blinds	Ordinary windows (Without special specifications)
	Clear and safety glass	
	50% minimum transmission for visible light	
Roof Insulation	Built-up with 25 mm R-14 board and high thermal mass insulation	Reinforced Concrete without special insulation
Lightning System	Optimum lighting distribution	Ordinary lighting distribution
	Automatic lighting controls	No automatic lighting controls
HVAC System	Variable Refrigerant Flow System (VRF)	Variable Air Volume System (VAV)

Hourly Analysis Program (HAP) is applied to analyze the comparison results. Green and traditional designs' annual energy consumption and cost are tabulated in table 3.

Table 3: *Comparison between annual green and traditional energy consumption and cost of green and traditional designs*

Compared Parameters	Green Design	Traditional Design
Total Annual Energy (kWh)	1,103,221	1,692,057
Total Annual ($)	89,051	136,581
Annual Energy Saving (kWh)	588,836	
Annual Cost Saving ($)	47,530	
Annual Energy / Cost Saving (%)	34.8 % ≈ 35 %	

From the previous table the energy saving per year is 588,836 kWh, the annual cost saving is 47,530 $ and the annual energy per cost saving in percentage is about 35%. Leadership in Energy and Environmental Design (LEED) rating system [83, 84] is applied to confirm the competency of the green building. LEED is considered one of the most widespread rating systems all over the world. The green building is awarded for 13 points. The comparison results show that the green building exhibits a massive saving in energy cost which proves its reliability and efficiency [87].

5 Conclusion

The state-of-the-art is divided into three main parts. The first part after the introduction covers the high voltage historical background, an overview on electrical power generation, transmission necessary apparatuses, distribution, possible electrical failures, and common protection traditions. Recent experimental and optimization techniques for obtaining high voltage precise measurements, detecting the failures before their occurrence, and robust protection methods adding to identifying the ideal electrical parameters of solar cells and modules are discussed in the second part. The future trends and up to date proposals in high voltage metrology are discussed in the third part. The hottest areas in the high voltage precision realm are debated such as the environmental economic load dispatch and energy saving trends to realize a clean environment with minimum energy consumption and lowest cost. In this concern, a green building is introduced as a case study.

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